Draft version September 15, 2010
Preprint typeset using LaTeX style emulateapj v. 11/10/09

A HOT JUPITER ORBITING THE 1.7 $M_\odot$ SUBGIANT HD 102956[1]

John Asher Johnson[2], Brendan P. Bowler[3], Andrew W. Howard[4], Gregory W. Henry[5], Geoffrey W. Marcy[4], Howard Isaacson[4], John Michael Brewer[6], Debra A. Fischer[6], Timothy D. Morton[2], Justin R. Crepp[2]

Draft version September 15, 2010

ABSTRACT

We report the detection of a giant planet in a 6.4950 day orbit around the 1.68 $M_\odot$ subgiant HD 102956. The planet has a semimajor axis $a = 0.081$ AU and minimum mass $M_P \sin i = 0.96$ $M_{\rm Jup}$. HD 102956 is the most massive star known to harbor a hot Jupiter, and its planet is only the third known to orbit within 0.6 AU of a star more massive than 1.5 $M_\odot$. Based on our sample of 137 subgiants with $M_\star > 1.45$ $M_\odot$ we find that 0.5–2.3% of A-type stars harbor a close-in planet ($a <$ 0.1 AU) with $M_P \sin i > 1$ $M_{\rm Jup}$, consistent with hot-Jupiter occurrence for Sun-like stars. Thus, the paucity of planets with $0.1 < a < 1.0$ AU around intermediate-mass stars may be an exaggerated version of the "period valley" that is characteristic of planets around Sun-like stars.

Subject headings: techniques: radial velocities—stars: individual (HD 102956)—planets and satellites: formation

1. INTRODUCTION

The current state of knowledge of planets around intermediate-mass ($M_\star \gtrsim 1.5$ $M_\odot$) stars is reminiscent of the general knowledge of exoplanets in 2001. At that time there were 32 planets known, mostly orbiting Sun-like stars. The distributions of semimajor axes and masses ($M_P \sin i$) of these early exoplanet discoveries, drawn from the Exoplanet Orbit Database[7], are shown in Figure 1, illustrating the prevalence of giant planets in unexpectedly close-in orbits[8]. As of 2010 May there are 31 planets known to orbit intermediate-mass stars ($M_\star > 1.5$ $M_\odot$), and the semimajor axes of planets in this new class was surprising, but for a different reason: there are no planets orbiting closer than 0.6 AU (Johnson et al. 2007; Sato et al. 2008). As Bowler et al. (2010) showed, the planet populations orbiting host stars on either side of 1.5 $M_\odot$ are distinct at the 4-σ level.

Close-in, Jovian planets are relatively easy to detect using radial velocities because of the larger amplitude they induce and the increased number of orbit cycles per observing time baseline. Their absence therefore cannot be due to an observational bias given the large population of planets at longer periods. Instead, it appears that stellar mass has a dramatic effect on the semimajor axis distribution of planets. However, it is not clear whether this effect is a reflection of the process of planet formation and migration, or instead related to the effects of the evolution of the host stars.

Stellar evolution may be an important factor because Doppler surveys of intermediate-mass stars are largely restricted to post-main-sequence targets. While massive, main-sequence stars are poor Doppler targets due to their rapid rotation ($V_{\rm rot} \sin i \gtrsim 50$ km s^{-1}; Lagrange et al. (2009)), their evolved counterparts on the giant and subgiant branches are much slower rotators ($V_{\rm rot} \sin i \lesssim$ 5 km s^{-1}) and therefore have the narrow absorption lines required for precise Doppler measurements. However, as stars evolve their atmospheres expand and may encroach upon the orbits of their planets. Simulations by Nordhaus et al. (2010), Carlberg et al. (2009) and Villaver & Livio (2009) have suggested that the engulfment planets by the expanding atmospheres of stars can account for the lack of close-in planets around K-giants and clump-giants (see also Sato et al. 2008).

While Doppler surveys have encountered a barren region around A stars inward of 0.6 AU, transit surveys have discovered two examples of hot Jupiters around intermediate-mass stars. OGLE2-TR-L9 and WASP-33 are 1.5 $M_\odot$ stars orbited by Jovian planets with semimajor axes $a = 0.041$ AU and 0.026 AU, respectively (Snellen et al. 2009; Collier Cameron et al. 2010). These detections demonstrate that close-in planets exist around A-type dwarfs, adding additional concern that the lack of planets close to evolved intermediate-mass stars is the result of stellar engulfment. Unfortunately, the complicated observational and selection biases inherent to ground-based, wide-field transit surveys make it difficult to measure accurate occurrence rates that can be meaningfully compared to those measured from Doppler surveys (Gaudi et al. 2005).

johnjohn@astro.berkeley.edu

[1] Based on observations obtained at the W.M. Keck Observatory, which is operated jointly by the University of California and the California Institute of Technology. Keck time has been granted by both NASA and the University of California.

[2] Department of Astrophysics, California Institute of Technology, MC 249-17, Pasadena, CA 91125; NASA Exoplanet Science Institute (NExScI)
[3] Institute for Astronomy, University of Hawai'i, 2680 Woodlawn Drive, Honolulu, HI 96822
[4] Department of Astronomy, University of California, Mail Code 3411, Berkeley, CA 94720
[5] Center of Excellence in Information Systems, Tennessee State University, 3500 John A. Merritt Blvd., Box 9501, Nashville, TN 37209
[6] Department of Astronomy, Yale University, New Haven, CT 06511

[7] http://exoplanets.org

[8] While unexpected based on the sample of one provided by the Solar System, the existence of short-period Jovian planets was predicted in at least one published instance prior to the discovery of the first hot Jupiter (Mayor & Queloz 1995). In 1952 Otto Struve mused, "...[T]here seems to be no compelling reason why the...planets should not, in some instances, be much closer to their parent star than is the case in the solar system. It would be of interest to test whether there are any such objects." (Struve 1952)

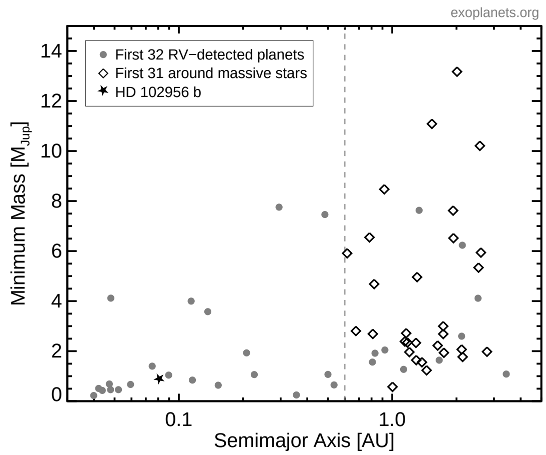

FIG. 1.— The semimajor axes and minimum masses ($M_P \sin i$) of the first 32 Doppler-detected planets (gray circles). The majority of these planets orbit stars with $M_\star < 1.5$ $M_\odot$, and the planets span a wide range of semimajor axes. Also shown are the first 31 Doppler-detected planets around massive stars ($M_\star > 1.5$ $M_\odot$; open diamonds), and the sole hot Jupiter, HD 102956 b (filled five-point star). Compared to the population of planets around Sun-like stars, there is a notable paucity of planets inward of 0.6 AU around the intermediate-mass stars.

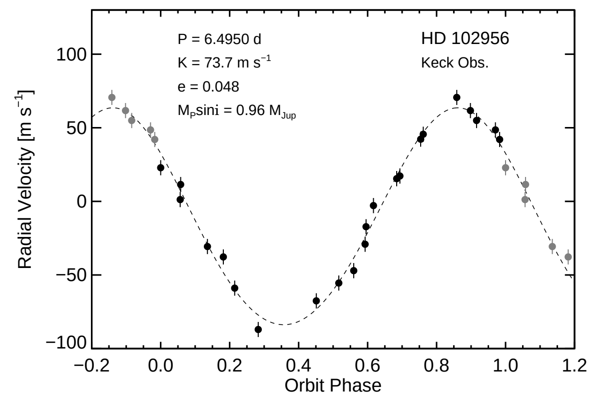

FIG. 2.— Doppler measurements of HD 102956 from Keck Observatory phased at the orbital period of the planet. The error bars are the quadrature sum of the internal measurement uncertainties and 5 m s^{-1} of jitter. The dashed line shows the best-fitting orbit solution of a single Keplerian orbit. The solution results in residuals with an rms scatter of 6.0 m s^{-1} and $\sqrt{\chi^2_\nu} = 1.35$, indicating a good fit to the data.

Among the various types of evolved stars, subgiants offer a unique view of the population of hot Jupiters around intermediate-mass stars. The radii of subgiants have inflated by only a factor of ≈ 2 compared to their main-sequence values. The simulations of Villaver & Livio (2009) show that planets with $a \gtrsim 0.1$ AU should be safe from the tidal influence of stars near the base of the RGB (see their Figure 2). It is only after stars start to ascend the RGB and have their radii expand to an appreciable fraction of an AU that tidal influences become important. The occurrence rates and semimajor axis distribution of close-in planets around subgiants should therefore be representative of the properties of planets around A-type dwarfs.

We are conducting a Doppler survey of intermediate-mass subgiants at Keck and Lick Observatories to study the effects of stellar mass on the physical properties and orbital architectures of planetary systems. Our survey has resulted in the detection of 14 planets around 12 intermediate-mass ($M_\star \gtrsim 1.5$ $M_\odot$) stars, and 4 additional planets around less-massive subgiants (Johnson et al. 2006, 2007, 2008; Bowler et al. 2010; Peek et al. 2009; Johnson et al. 2010a, Johnson et al. 2010b, submitted). In this Letter we report the first Doppler-detected planet within 0.6 AU of a "retired" (former) A star: a hot Jupiter around a 1.68 $M_\odot$ subgiant.

2. STELLAR PROPERTIES, RADIAL VELOCITIES AND ORBIT

HD 102956 (=HIP 57820) is listed in the *Hipparcos* Catalog with $V = 8.02$, $B - V = 0.971$, a parallax–based distance of 126 pc, and an absolute magnitude $M_V = 2.5$ (ESA 1997). Like most subgiants, HD 102956 is chromospherically–quiet with an average $S = 0.17 \pm 0.02$ and $\log R'_{HK} = -5.09$ on the Mt. Wilson scale (Wright et al. 2004). We used the LTE spectral synthesis described by Valenti & Fischer (2005) and Fischer & Valenti (2005) to estimate the spectroscopic properties. To constrain the low surface gravities of the evolved stars we used the iterative scheme of Valenti et al. (2009), which ties the SME-derived value of $\log g$ to the gravity inferred from the Yonsei-Yale (Y^2) stellar models. Our SME analysis gives $T_{\rm eff} = 5054 \pm 44$ K, [Fe/H] $= +0.19 \pm 0.04$, $\log g = 3.5 \pm 0.06$ and $V_{\rm rot} \sin i = 0.30 \pm 0.5$ km s^{-1}. We compared the star's temperature, luminosity and metallicity to the Y^2 stellar model grids to estimate a stellar mass $M_\star = 1.68 \pm 0.11$ $M_\odot$ and radius $R_\star = 4.4 \ \pm 0.07$ $R_\odot$. All of the stellar properties are summarized in Table 1.

We began monitoring the radial velocity of HD 102956 in 2007 April and we have gathered a total of 22 measurements. After two seasons of observing we noticed RV variability with an rms scatter of 41 m s^{-1}, which is much larger than the scatter predicted by the measurement uncertainties and jitter levels typical of subgiants (Fischer et al. 2003; Wright 2005; Johnson et al. 2010a). Table 2 lists our RV measurements, times of observation and internal errors (without jitter). Johnson et al. (2010a) estimate a typical jitter of 5 m s^{-1} based on their analysis of 382 RV observations of 72 stable subgiants observed at Keck with HIRES. We add this jitter estimate in quadrature to the internal measurement errors to ensure proper weighting of the data in our orbit analysis.

To search for the best-fitting orbit we used the partially-linearized Keplerian fitting code `RVLIN`[9] described by Wright & Howard (2009). As an alternative to a periodogram analysis, we first stepped through a grid of orbital periods sampled from 1 to 100 days in 5000 equal, logarithmically-spaced intervals. At each step we fixed the period, searched for the best-fitting orbit and recorded the resulting[10] $\sqrt{\chi^2_\nu}$. We found a minimum

[9] http://exoplanets.org/code/

[10] We use $\sqrt{\chi^2_\nu}$ to indicate the factor by which the observed scatter about the best-fitting model differs from our expectation based on the measurement errors. Thus, the scatter about our model is a factor of 1.35 larger than our average error bar.

TABLE 1
STELLAR PROPERTIES AND ORBITAL SOLUTION FOR HD 102956

Parameter	Value
V	8.02 ± 0.05
$B - V$	0.971 ± 0.01
Distance (pc)	126 ± 13
M_V	2.5 ± 0.2
[Fe/H]	$+0.19 \pm 0.04$
$T_{\rm eff}$ (K)	5054 ± 44
$V_{\rm rot} \sin i$ (km s^{-1})	0.30 ± 0.5
$\log g$	3.5 ± 0.06
$M_\star$ ($M_\odot$)	1.68 ± 0.11
$R_\star$ ($R_\odot$)	4.4 ± 0.1
$L_\star$ ($R_\odot$)	11.6 ± 0.5
$\log R'_{HK}$	-5.09
Age (Gyr)	2.3 ± 0.5
P (days)	6.4950 ± 0.0004
K (m s^{-1})	73.7 ± 1.9
e	0.048 ± 0.027
T_P (Julian Date)	2455346 ± 0.7
ω (degrees)	12 ± 40
$M_P \sin i$ ($M_{\rm Jup}$)	0.96 ± 0.05
a (AU)	0.081 ± 0.002
$R_\star/a$	0.253 ± 0.008
$N_{\rm obs}$	22
rms (m s^{-1})	6.0
$\sqrt{\chi^2_\nu}$	1.35

($\sqrt{\chi^2_\nu} = 1.15$) at periods near 6.5 days. The next lowest minimum ($\sqrt{\chi^2_\nu} = 1.98$) occurs at $P = 3.47$ days. However, with a best-fitting eccentricity of 0.95, the orbit solution is clearly unphysical.

We then allowed the period to float in our `RVLIN` analysis with an initial guess of $P = 6.5$ days, and found that a single-planet Keplerian model with a period $P = 6.4950 \pm 0.0004$ days, eccentricity $e = 0.048 \pm 0.027$ and velocity semiamplitude $K = 73.7 \pm 1.9$ m s^{-1}. The fit produces RV residuals with a root-mean-squared (rms) scatter of 6.0 m s^{-1} and reduced $\sqrt{\chi^2_\nu} = 1.35$, indicating an acceptable fit. We used the false-alarm analysis of Howard et al. (2009) to calculate FAP < 0.001 (see also Johnson et al. 2010b). The resulting minimum planet mass is $M_P \sin i = 0.96$ $M_{\rm Jup}$, and the semimajor axis is $a = 0.081$ AU. The best-fitting solution is shown in Figure 2, where the plotted error bars are the quadrature sum of internal errors and 5 m s^{-1} of jitter.

After identifying the best-fitting model, we use a Markov-Chain Monte Carlo (MCMC) algorithm to estimate the parameter uncertainties (See, e.g. Ford 2005; Winn et al. 2007; Bowler et al. 2010). MCMC is a Bayesian inference technique that uses the data to explore the shape of the likelihood function for each parameter of an input model. At each step, one parameter is selected at random and altered by drawing a random variate from a normal distribution. If the resulting χ^2 (not reduced by the number of free parameters ν) value for the new trial orbit is less than the previous χ^2 value, then the trial orbital parameters are added to the chain. If not, then the probability of adopting the new value is set by the difference in χ^2 from the previous and current trial steps. If the current trial is rejected then the parameters from the previous step are adopted. We adjusted the width of the normal distributions from which the steps are drawn until we achieved a 30–40% acceptance rate in each parameter. The resulting "chains" of parameters form the posterior probability distribution, from which we select the 15.9 and 84.1 percentile levels in the cumulative distributions as the "one-sigma" confidence limits. In most cases the posterior probability distributions were approximately Gaussian. The orbital parameters and their uncertainties are listed in Table 1.

As an additional check on the nature of the RV variations, we acquired photometric observations of HD 102956 with the T3 0.4 m automatic photometric telescope (APT) at Fairborn Observatory. A brief description of the T3 data acquisition and reduction procedures, as well as the utility of the APT observations for eliminating false positive detections, can be found in Johnson et al. (2010a).

The APT collected two dozen observations in the Johnson V and B photometric bands between 2010 May 30 and June 23, near the end of the 2010 observing season. The V observations scatter about their mean with a standard deviation of 0.0037 mag, consistent with T3's measurement precision for a single observation (e.g., Henry et al. 2000, Tables 2–3). A least-squares sine fit on the 6.4948-day radial velocity period yielded a semi-amplitude of 0.0012 ± 0.0010 mag. Identical results were obtained for the B observations. This tight upper limit to photometric variability provides strong support for the planetary interpretation of the radial velocity variations.

3. THE FRACTION OF INTERMEDIATE-MASS STARS WITH HOT JUPITERS

Our Keck and Lick Doppler surveys of subgiant stars have time baselines of 3 and 6 years, respectively, and the majority of the target stars have more than 6 observations with jitter-limited measurement precision ranging from 3–6 m s^{-1}. Our precision, cadence and time baseline provide us with the opportunity to assess the fraction of intermediate-mass stars with hot Jupiters, which we define as planets with $a < 0.1$ AU. This definition is somewhat arbitrary, but it is consistent with definitions widely used by other studies of hot Jupiters, which typically focus on Solar-mass stars and periods $P \lesssim 10$ days. The most comprehensive study of this kind is that of Cumming et al. (2008), who measure an occurrence rate of $f = 0.004 \pm 0.003$ for $a < 0.1$ AU, $M_P \sin i \geq 1$ $M_{\rm Jup}$ and primarily stars with masses $M_\star < 1.4$ $M_\odot$. Their reported planet occurrence is consistent with $f < 0.01$ at 95% confidence.

Within our sample we restrict our analysis to stars with $M_\star > 1.45$ $M_\odot$ (the evolved counterparts of A-type stars), $N_{\rm obs} > 3$, $V_{\rm rot} \sin i < 20$ km s^{-1} and no evidence of double-lines indicative of an SB2. Our sample contains 137 stars that meet these criteria. For each star we first perform a periodogram analysis and use `RVLIN` to search for orbit solutions near the strongest periodicities using the same technique described by Marcy et al. (2005). We then evaluate the FAP by estimating the likelihood of improving χ^2_ν over that of a linear fit (see Howard et al. 2009, for further details). For solutions with FAP < 0.01, we record the rms of the residuals about the best-fitting orbit. For larger FAP values we record the rms about the best-fitting linear fit to the RVs.

Next, we measure the largest velocity semiamplitude $K_{\rm up}$ that is consistent with the observed rms scatter for

TABLE 2
RADIAL VELOCITIES FOR HD 102956

JD -2440000	RV ($\mathrm{m\ s^{-1}}$)	Uncertainty ($\mathrm{m\ s^{-1}}$)
14216.805	11.40	1.18
14429.150	5.77	1.39
14866.114	37.10	1.30
14986.851	-58.52	1.27
15014.772	59.14	1.07
15016.870	-49.20	1.13
15284.917	-79.04	1.34
15285.993	-14.32	1.25
15313.915	43.48	1.25
15314.828	-10.25	1.18
15343.795	-66.93	1.17
15344.885	3.98	1.35
15350.786	-40.57	1.27
15351.880	34.14	1.19
15372.804	30.58	1.16
15373.796	-42.13	1.22
15374.753	-98.50	1.10
15376.783	-28.67	1.12
15377.812	30.78	1.10
15378.749	50.22	1.12
15379.787	0.00	1.13
15380.805	-70.40	1.13

simulated planets of various periods. Our method is similar to that of Lagrange et al. (2009) and Bowler et al. (2010). For each star we sample a range of orbital periods corresponding to semimajor axes $0.04 \leq a \leq 0.10$ AU[11]. At each fixed period we generate a sample of 3000 simulated orbits with random phases and circular orbits sampled at the actual times of observation. For each simulated orbit we also add 5 $\mathrm{m\ s^{-1}}$ of random noise to simulate jitter. We then record the distribution of 3000 simulated velocity rms values and compare the distribution to the rms of the measurements. Finally, we adjust K until the measured rms is less than that of 99.7% of the simulated orbits, and record the semiamplitude as K_{up} at that period.

Repeating this procedure for all 137 stars provides a measure the completeness of our survey for planets above a given $M_P \sin i$ at each semimajor axis sampled in our simulations. Figure 3 shows contours of constant completeness for our sample, together with the position of HD 102956, demonstrating that we are 95% complete for $M_P \sin i > 1$ $\mathrm{M_{Jup}}$ and $a < 0.1$ AU.

Since each detection or nondetection of a hot Jupiter represents a Bernoulli trial, the fraction of stars with planets in our sampled range is given by the binomial distribution $\mathrm{P}(f|k, N) \propto f^k(1-f)^{N-k}$, where $N = 137$ is the number of target stars containing k detections. For our sample we measure an occurrence rate of $f = 1.2^{+1.2}_{-0.7}$, or $f < 0.034$ at 95% confidence for $M_P \sin i \geq 0.9$ $\mathrm{M_{Jup}}$, which includes a single detection, HD 102956 b with $M_P \sin i = 0.96 \pm 0.05$. Restricting our analysis to planets more massive than 1 $\mathrm{M_{Jup}}$ we find $f < 0.025$ at 95% confidence.

Based on their survey of main-sequence A-type stars, Lagrange et al. (2009) reported no planets with $P <$ 10 days among a sample of 50 stars[12], or $f < 0.05$ at 95% confidence. However, because their early-type stars are such rapid rotators, their achievable velocity precision only allowed them to rule out planets with $M_P \sin i \gtrsim 8$ $\mathrm{M_{Jup}}$. Thus, our estimate of the fraction of massive stars with hot Jupiters represents a significant refinement compared to the previous constraints. However, our sample size is still too small to provide a meaningful comparison with the planet fraction measured by Cumming et al. (2008) for less massive stars. An extension of our subgiants survey to the Southern sky is therefore warranted, and is currently underway at the Anglo Australian Observatory (R. Wittenmyer, private communication). Additional constraints will be provided by the *Kepler* space-based transit survey (Borucki et al. 2004).

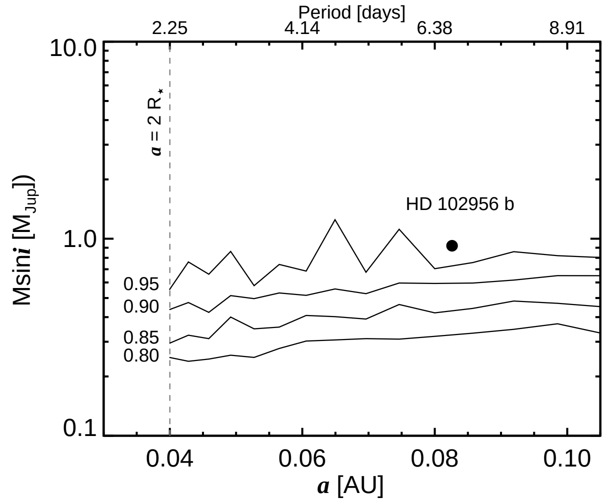

FIG. 3.— Detection limits of the Keck Doppler survey of intermediate-mass subgiants as a function of semimajor axis. The contours indicate the minimum planet mass detectable with a given fractional completeness, which is labeled to the left of each contour. The vertical dashed line shows the semimajor axis that is roughly equal to 2 stellar radii, assuming $R_\star = 4$ $\mathrm{R_\odot}$, which is typical of stars in the Keck survey. The position of HD 102956 b is marked with a solid circle.

4. SUMMARY

We report the discovery of a hot Jupiter ($e = 0.048 \pm 0.027$, $M_P \sin i = 0.96$ $\mathrm{M_{Jup}}$, $P = 6.4950$ days) orbiting the subgiant HD 102956. At $M_\star = 1.68$ $\mathrm{M_\odot}$, HD 102956 is the most massive star known to harbor a hot Jupiter, and this short-period system is the first detected as part of a Doppler survey of evolved, intermediate-mass stars.

The existence of this planet demonstrates that the observed population of close-in planets around subgiants is largely representative of the "primordial" planet population, in that close-in planets have not been adversely affected by the relatively mild, post-main-sequence expansion of their host stars. This aspect of subgiants, together with their jitter-limited RV precision of ≈ 5 $\mathrm{m\ s^{-1}}$, makes them ideally suited for studying the properties of short-period planets with a wide range of minimum

[11] The lower limit of 0.04 AU corresponds to $a/R_\star = 2$ for a typical $M_\star = 1.7$ $\mathrm{M_\odot}$ subgiant with $R_\star = 4$ $\mathrm{R_\odot}$, which is the smallest scaled semimajor axis among the known hot Jupiters listed in the Exoplanet Orbit Database.

[12] Lagrange et al. (2009) do not report stellar masses, but instead classify stars based on $B-V$ colors. We selected stars from their Table 4 with colors $0.0 < B-V < 0.3$ as representative of main-sequence A-stars in our mass range ($M_\star > 1.45$ $\mathrm{M_\odot}$).

masses around intermediate-mass stars.

Based on our current stellar sample we estimate that 0.5–2.3% of A-type stars harbor a planet with $a < 0.1$ AU and $M_P \sin i > 1$ M_{Jup}, compared to the 0.4% occurrence rate around Sun-like stars (Cumming et al. 2008). While planets with $a < 1$ AU are unusually rare around A stars, it is possible that there exists a population of hot Jupiters ($a < 0.1$ AU) around intermediate-mass stars comparable to what is found around Sun-like stars. If so, then the close-in desert around A stars may simply be an exaggerated version of the "period valley" observed around Sun-like stars, marked by a deficit of planets with periods ranging from roughly 10–100 days, a sharp increase in the number of detected planets beyond 1 AU, and a pile-up near $P = 3$ day (Udry & Santos 2007; Cumming et al. 2008; Wright et al. 2009). Doppler surveys of a larger number of massive subgiants, together with careful analyses of detections from transit surveys, will test this possibility.

We gratefully acknowledge the efforts and dedication of the Keck Observatory staff, especially Grant Hill, Scott Dahm and Hien Tran for their support of HIRES and Greg Wirth for support of remote observing. We are also grateful to the time assignment committees of NASA, NOAO, Caltech, and the University of California for their generous allocations of observing time. A. W. H. gratefully acknowledges support from a Townes Post-doctoral Fellowship at the U. C. Berkeley Space Sciences Laboratory. G. W. M. acknowledges NASA grant NNX06AH52G. G. W. H acknowledges support from NASA, NSF, Tennessee State University, and the State of Tennessee through its Centers of Excellence program. Finally, the authors wish to extend special thanks to those of Hawaiian ancestry on whose sacred mountain of Mauna Kea we are privileged to be guests. Without their generous hospitality, the Keck observations presented herein would not have been possible.

REFERENCES

Borucki, W., Koch, D., Boss, A., Dunham, E., Dupree, A., Geary, J., Gilliland, R., Howell, S., Jenkins, J., Kondo, Y., Latham, D., Lissauer, J., & Reitsema, H. 2004, ESA Special Publication, Vol. 538, The Kepler mission: a technical overview, 177–182
Bowler, B. P., Johnson, J. A., Marcy, G. W., Henry, G. W., Peek, K. M. G., Fischer, D. A., Clubb, K. I., Liu, M. C., Reffert, S., Schwab, C., & Lowe, T. B. 2010, ApJ, 709, 396
Carlberg, J. K., Majewski, S. R., & Arras, P. 2009, ApJ, 700, 832
Collier Cameron, A., Guenther, E., Smalley, B., McDonald, I., Hebb, L., Andersen, J., Augusteijn, T., Barros, S. C. C., Brown, D. J. A., Cochran, W. D., Endl, M., Fossey, S. J., Hartmann, M., Maxted, P. F. L., Pollacco, D., Skillen, I., Telting, J., Waldmann, I. P., & West, R. G. 2010, ArXiv:1004.455
Cumming, A., Butler, R. P., Marcy, G. W., Vogt, S. S., Wright, J. T., & Fischer, D. A. 2008, PASP, 120, 531
ESA, . 1997, VizieR Online Data Catalog, 1239, 0
Fischer, D. A., Marcy, G. W., Butler, R. P., Vogt, S. S., Henry, G. W., Pourbaix, D., Walp, B., Misch, A. A., & Wright, J. T. 2003, ApJ, 586, 1394
Fischer, D. A. & Valenti, J. 2005, ApJ, 622, 1102
Ford, E. B. 2005, AJ, 129, 1706
Gaudi, B. S., Seager, S., & Mallen-Ornelas, G. 2005, ApJ, 623, 472
Henry, G. W., Fekel, F. C., Henry, S. M., & Hall, D. S. 2000, ApJS, 130, 201
Howard, A. W., Johnson, J. A., Marcy, G. W., Fischer, D. A., Wright, J. T., Henry, G. W., Giguere, M. J., Isaacson, H., Valenti, J. A., Anderson, J., & Piskunov, N. E. 2009, ApJ, 696, 75
Johnson, J. A., Fischer, D. A., Marcy, G. W., Wright, J. T., Driscoll, P., Butler, R. P., Hekker, S., Reffert, S., & Vogt, S. S. 2007, ApJ, 665, 785
Johnson, J. A., Howard, A. W., Bowler, B. P., Henry, G. W., Marcy, G. W., Wright, J. T., Fischer, D. A., & Isaacson, H. 2010a, PASP, 122, 701
Johnson, J. A., Howard, A. W., Marcy, G. W., Bowler, B. P., Henry, G. W., Fischer, D. A., Apps, K., Isaacson, H., & Wright, J. T. 2010b, PASP, 122, 149
Johnson, J. A., Marcy, G. W., Fischer, D. A., Henry, G. W., Wright, J. T., Isaacson, H., & McCarthy, C. 2006, ApJ, 652, 1724
Johnson, J. A., Winn, J. N., Narita, N., Enya, K., Williams, P. K. G., Marcy, G. W., Sato, B., Ohta, Y., Taruya, A., Suto, Y., Turner, E. L., Bakos, G., Butler, R. P., Vogt, S. S., Aoki, W., Tamura, M., Yamada, T., Yoshii, Y., & Hidas, M. 2008, ApJ, 686, 649
Lagrange, A., Desort, M., Galland, F., Udry, S., & Mayor, M. 2009, A&A, 495, 335
Marcy, G. W., Butler, R. P., Vogt, S. S., Fischer, D. A., Henry, G. W., Laughlin, G., Wright, J. T., & Johnson, J. A. 2005, ApJ, 619, 570
Mayor, M. & Queloz, D. 1995, Nature, 378, 355
Nordhaus, J., Spiegel, D. S., Ibgui, L., Goodman, J., & Burrows, A. 2010, MNRAS, 1164
Peek, K. M. G., Johnson, J. A., Fischer, D. A., Marcy, G. W., Henry, G. W., Howard, A. W., Wright, J. T., Lowe, T. B., Reffert, S., Schwab, C., Williams, P. K. G., Isaacson, H., & Giguere, M. J. 2009, PASP, 121, 613
Sato, B., Izumiura, H., Toyota, E., Kambe, E., Ikoma, M., Omiya, M., Masuda, S., Takeda, Y., Murata, D., Itoh, Y., Ando, H., Yoshida, M., Kokubo, E., & Ida, S. 2008, PASJ, 60, 539
Snellen, I. A. G., Koppenhoefer, J., van der Burg, R. F. J., Dreizler, S., Greiner, J., de Hoon, M. D. J., Husser, T. O., Krühler, T., Saglia, R. P., & Vuijsje, F. N. 2009, A&A, 497, 545
Struve, O. 1952, The Observatory, 72, 199
Udry, S. & Santos, N. C. 2007, ARA&A, 45, 397
Valenti, J. A., Fischer, D., Marcy, G. W., Johnson, J. A., Henry, G. W., Wright, J. T., Howard, A. W., Giguere, M., & Isaacson, H. 2009, ApJ, 702, 989
Valenti, J. A. & Fischer, D. A. 2005, ApJS, 159, 141
Villaver, E. & Livio, M. 2009, ApJ, 705, L81
Winn, J. N., Holman, M. J., & Fuentes, C. I. 2007, AJ, 133, 11
Wright, J. T. 2005, PASP, 117, 657
Wright, J. T. & Howard, A. W. 2009, ApJS, 182, 205
Wright, J. T., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2004, ApJS, 152, 261
Wright, J. T., Upadhyay, S., Marcy, G. W., Fischer, D. A., Ford, E. B., & Johnson, J. A. 2009, ApJ, 693, 1084